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## **Top Quark Physics**

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# TOP QUARK PHYSICS

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Most of the material presented in this report, comes from contributions to the parallel session PL20 of this conference. We summarise the experimental results of direct production of Top quarks, coming from the CDF and D0 Collaborations at Fermilab, and compare these results to what one expects within current theoretical understanding. Particular attention is given to new results such as all hadronic modes of  $t\bar{t}$  decay. As far as the mass is concerned, a comparison is made with precision measurements of related quantities, coming from LEP and other experiments. An attempt is made to look at the medium-term future and understand which variables and with what accuracy one can measure them with increased integrated luminosity.

## 1 Introduction

One question which came up more than once during the conference was: "now that the top quark has been found what kind of physics can we do with it?" We are in a early stage but it is clear that a number of quantities will be measured with increasing precision. For example studies are underway to observe W's from top decaying into tau channels. Other quantities of interest are :

The production cross-section. A deviation from the QCD prediction would hint of something else being produced together with  $t\bar{t}$  pairs,

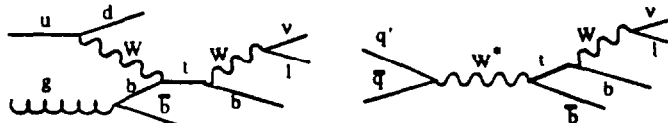
The top mass. This is presently known with large statistical and systematic errors. The reduction of these errors, combined with better knowledge of the mass of the W helps to constrain the mass of the Higgs.

Branching ratios. At this time one assumes that all tops decay into W and b. A measurement of the actual value of this branching ratio would allow us to evaluate  $V_{tb}$  in the unitarity triangle.

The  $P_t$  distribution is sensitive to nonleading production mechanisms other than  $q\bar{q} \rightarrow t\bar{t}$ .

One has to check, with precision, for deviations from phase space in the  $M_{t\bar{t}}$  distribution. Bumps in this distribution would be evidence of some exotic production.

Single top production. The so called "W-gluon fusion" and s-channel  $W^*$  production processes will be actively searched for even though current calculations lead us to believe that the cross sections are too small.



The first, in particular, is related in a simple way to the width of the top and eventually should provide the most accurate value for it. The cross-sections for these and other relevant processes at 1800 GeV are given in Fig. 1.

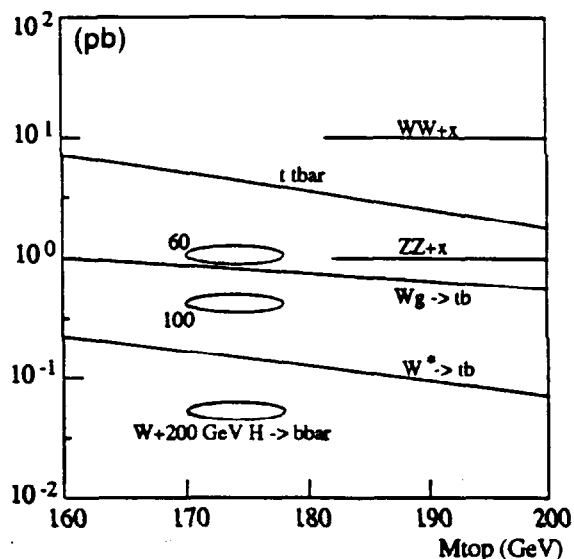


Figure 1: Cross sections as a function of  $M_{top}$ .

## 2 Cross-section

The published CDF and D0 results <sup>1,2</sup> are presented in a graph of cross-section vs mass, Fig. 2. Several other experimental values of the mass and the cross-section were presented during the conference, based on the analysis of other decay channels of the top or different event selections and will be quoted in the following. Although consistent with the main result, typically uncertainties of these analyses are larger and do not qualitatively change the picture. The experimental results are compared (and within errors agree) with a calculation of the cross-section presented in this conference by Ed Berger <sup>3</sup>. This is a resummation using a perturbative approach avoiding an infrared cut-off. The result only differs by 10 % from

the previous calculation of Laenen et al. <sup>4</sup> but the uncertainty associated to different choices of the parameters is reduced. A relatively light Higgs could produce a final state enhancement of 5÷10 % in the cross section at threshold, as pointed out in this conference by M. Jezabek <sup>5</sup> in his report on the physics potentiality of a e+e- collider.

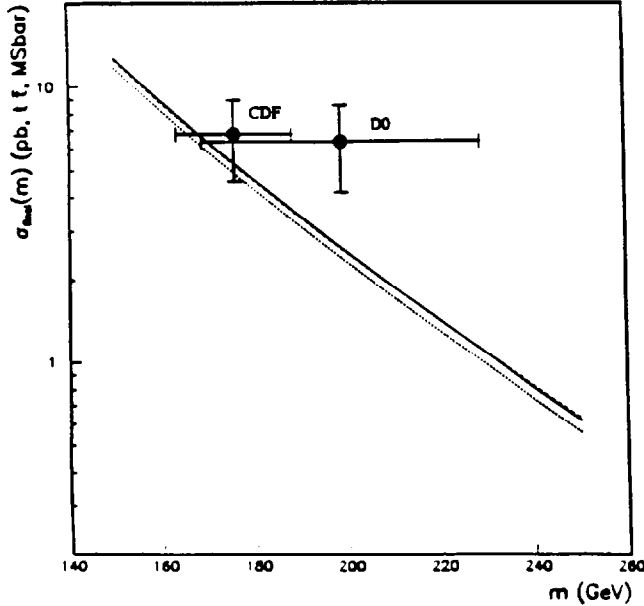


Figure 2:  $t\bar{t}$  production cross section as function of  $M_{top}$

### 3 Experimental results

This section follows the traditional sequence of presenting the results according to the method of top selection. In the "dilepton channel", the W's from each top decay into an electron or muon. One does not expect this channel to be rich in statistics but it is particularly clean. In the "lepton plus jets channel", one W decays semileptonically and the other into two jets. This channel has a higher QCD background but the larger statistical sample allows further selective cuts. One possibility is to select a b-enriched sample, presumably coming from top. Another is to look at kinematic variables related to an excess of transverse energy, sometimes combined with aplanarity. Simulations show that the distributions of these variables from top events are well separated from QCD background. In other words one looks at particularly "spectacular" events to select a clean  $t\bar{t}$  sample. In the "all hadron channel", both W's decay into a jet pair giving six jets in the final state. This channel, potentially the richest in statistics, is affected by the highest QCD background. Nevertheless, using secondary vertex tags of b's one can select a sample in which the top is observable.

#### 3.1 Dilepton analysis

Based on 45 pb<sup>-1</sup> D0 selects the correct topology and observes two events in the  $e\mu$  channel and one in  $\mu\mu$ . In Fig.3 these are presented as a function of the scalar sum of all observable  $E_t$ ; in the same picture is shown what one expects for top and for background and the chosen cut to separate the two. After this result D0 registered two additional dilepton events and from these five they determine a "most probable" value of the mass  $145 \pm 25 \pm 20$  GeV/c<sup>2</sup>.

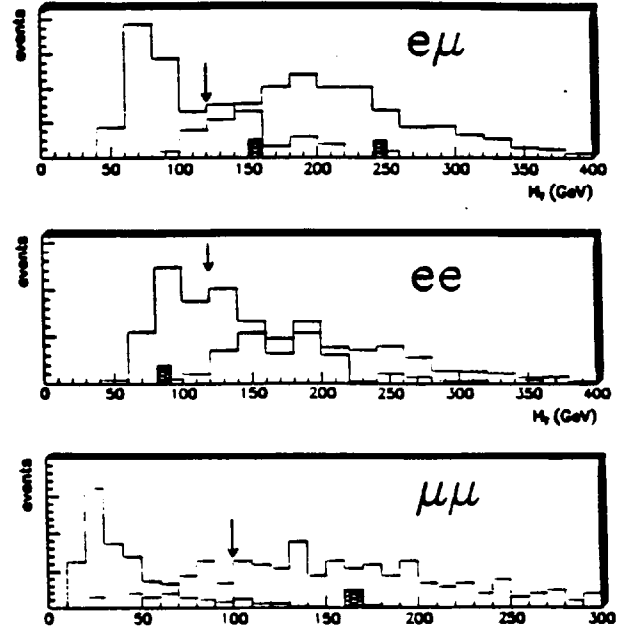


Figure 3: D0 dilepton candidates. Expected background and signal region are indicated as histograms.

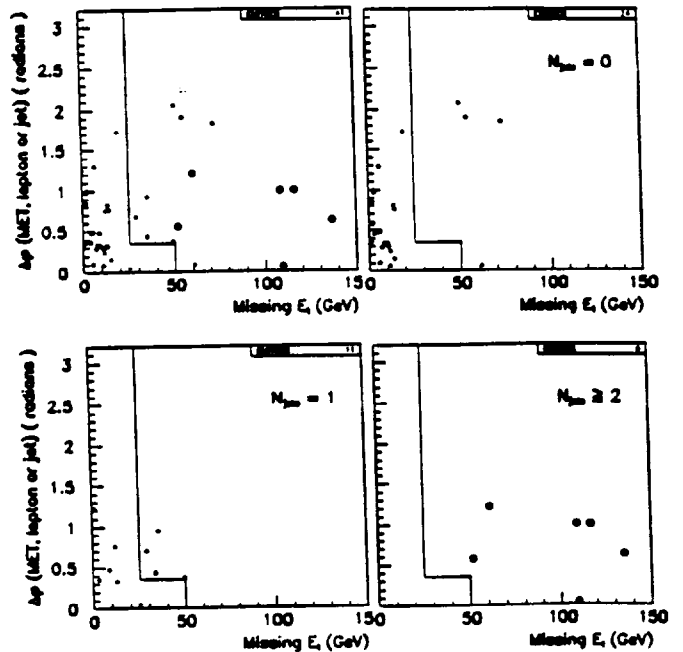


Figure 4: CDF  $e\mu$  candidates for different selection of jet multiplicities.

An update to  $100 \text{ pb}^{-1}$  was presented by CDF<sup>1</sup>. The results are given in Fig.4 where the six  $e\mu$  events are shown as a function of missing Et and isolation. The four cases are: the first, for the inclusive sample and the others when one requires 0, 1 and 2 or more jets. It is evident that the cuts (indicated in the figure) used to reject backgrounds are almost superfluous when the correct topology is chosen. CDF has in addition one more event in the  $ee$  channel and two in the  $\mu\mu$  channel.

### 3.2 Lepton plus jet analysis

The topology for this channel is a high Et electron or muon, a sizeable missing Et and four jets. If one selects events according to these criteria the signal to background is poor, see open points in Fig.5 and 6. A way to improve the signal to background is to make use of the fact that two out of four jets should be b's. CDF has a "secondary vertex detector, SVX" that in 45% of cases tags a single b and in 70% of cases tags at least one out of two. It can be seen in Fig.5 that in events with a W plus one or two jets one observes the expected tagging rate, whereas for a W plus three, four or more jets the tag rates are substantially higher (40 tags with 10 background expected). The hypothesis that the selected sample is indeed rich in b's is confirmed by the fact that the proper life time distribution measured for the selected events agrees with the known b lifetime (see the inset of Fig.5).

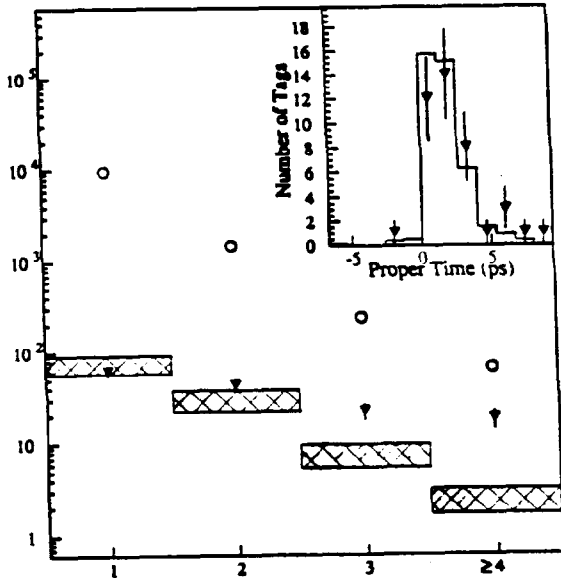


Figure 5: CDF event distribution as function of jet multiplicity. Open points before tags, triangles SVX tagged events, shaded area expected background. The inset shows the lifetime distribution for  $\geq 3$  jets tagged events.

An alternative way is to look if the jets contains another lepton typical of a flavour chain decay of the b. Also in this way, as shown in Fig 6 one sees an excess in the sample with 3 and four jets. This second technique is also used by D0 and the results are shown in Fig.7. Again one sees that by increasing jet minimum multiplicity there is an increase in the tag rate.

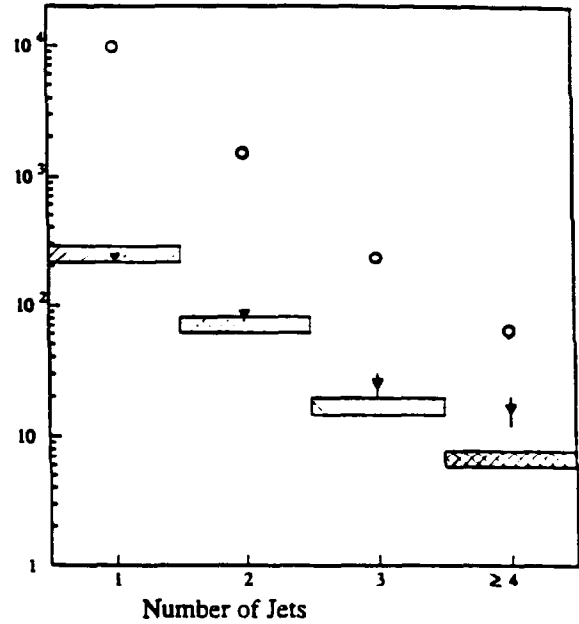


Figure 6: CDF event distribution as function of jet multiplicity. Open points before tags, triangles SLT tagged events, shaded area expected background.

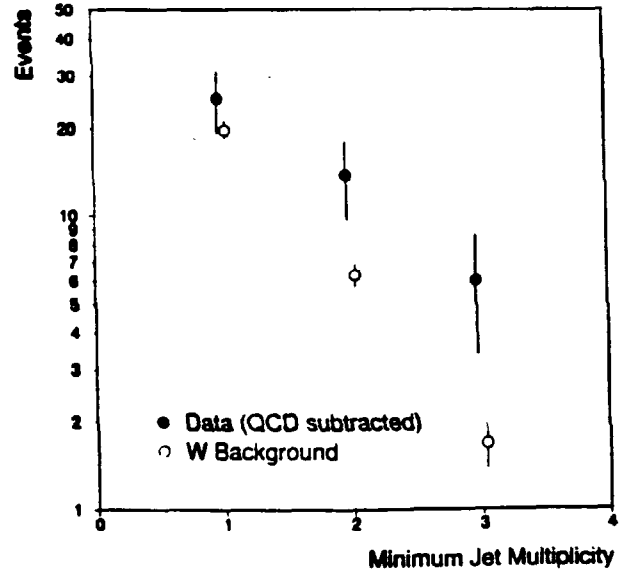


Figure 7: D0 event distribution as function of inclusive jet multiplicity. Full circles before tagging, open circles after soft lepton tagging.

Out of these samples both CDF and D0 work out cross sections and masses already published <sup>1,2</sup> and shown in Fig. 2. In Fig. 8 D0 presents a comparison of the selected sample with what they expect for top and for background with and without a cut in  $H_t$ . Tagged events are shaded. Similarly in Fig.9 and 10 the data from CDF are presented for tagged events with W+3 jets and W+4jets; a comparison with the signal and expected background is superimposed.

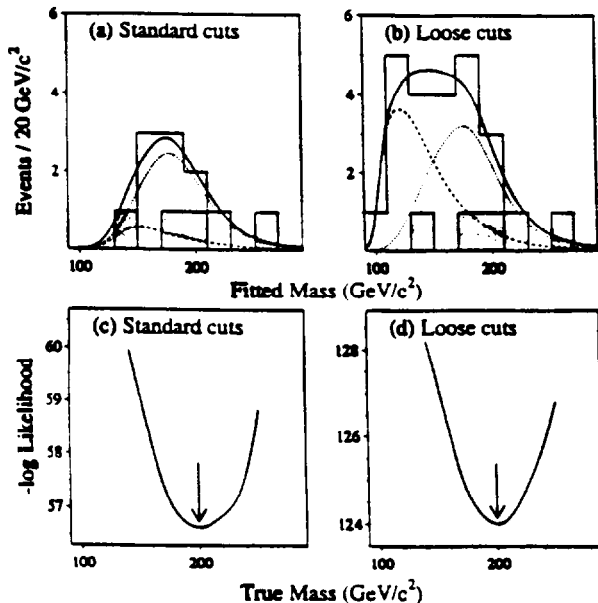


Figure 8: D0 mass reconstruction. a) and b) data (tagged events are shaded). c) and d) likelihood (the arrows indicate the chosen mass value).

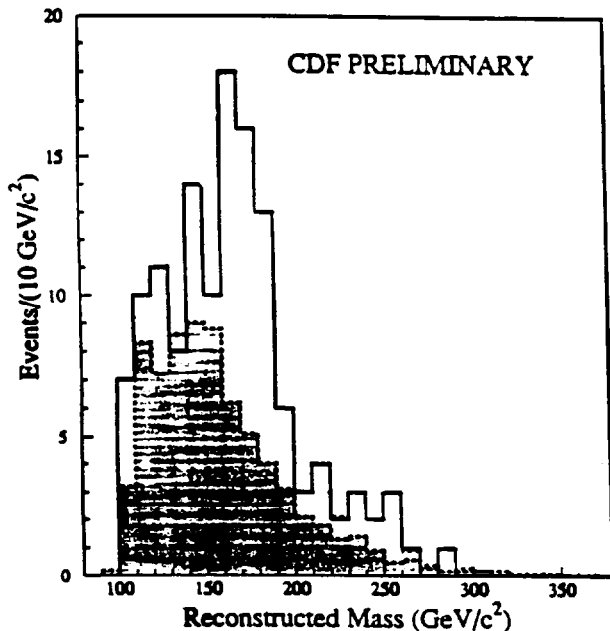


Figure 9: CDF mass distribution for events before tagging. Shaded area is the expected background.

With the 32 events of Fig. 10 it is possible to reconstruct the mass of the  $t\bar{t}$  system. The result is shown in Fig. 11, and compared with what one expects as background.

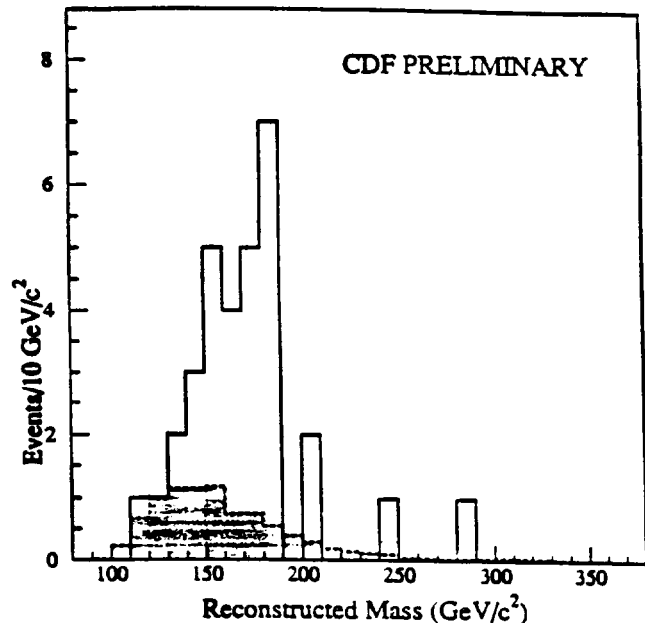


Figure 10: CDF mass distribution for tagged events. Shaded area is the expected background.

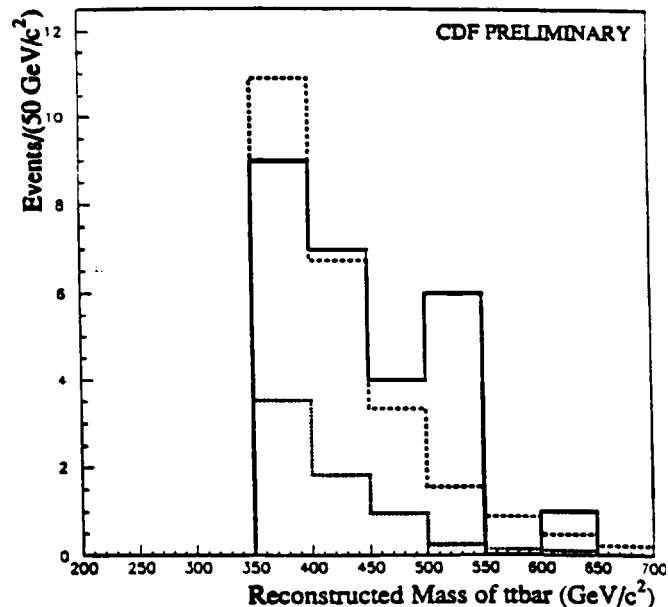


Figure 11: CDF  $t\bar{t}$  invariant mass distribution. Solid line data, dashed line top Monte Carlo, dotted line estimate background.

An important check is to show that the selected sample indeed contains W's. Fig. 12a,b are lego plots  $M_{top} \times M_W$  (dijet) of what D0 expects for top and background; the region of the signal is highlighted.

The data, Fig.12c, are consistent with a mixture of the two and the excess is at the right value of the W mass. More exclusively, out of the 32 CDF tagged events  $W+4$  jets, there are 8 which have double tags. For these events, the jets may be assigned unambiguously. Fig.13 shows in a scatter diagram  $M_{T_W}(l\nu)$  vs  $M_W(\text{dijet})$  with the mass constraints released. The data clusters in the expected region.

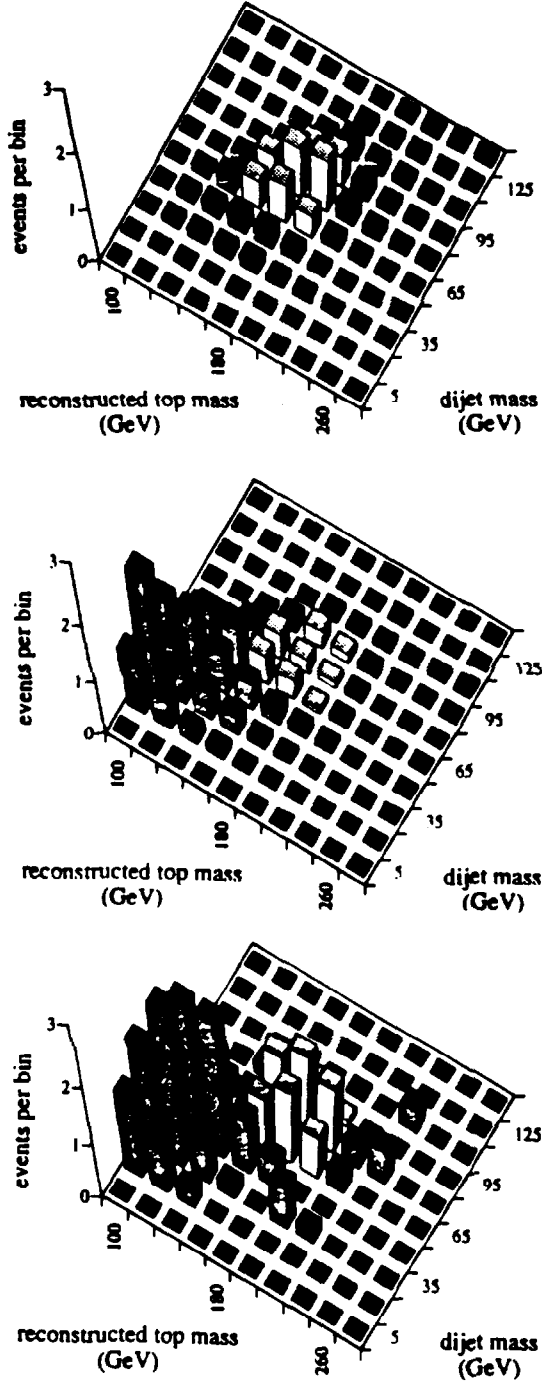


Figure 12: D0 reconstructed top mass versus reconstructed W (dijet) mass.

As mentioned above there are complementary approaches to the selection of b-tagged events, namely selecting events with particularly large transverse energies and possibly aplanarity. If for example one defines a relative likelihood as:

$$L_{rel} = \frac{\frac{1}{\sigma} \frac{d\sigma^{tf}}{dE_{T_2}} \times \frac{1}{\sigma} \frac{d\sigma^{tf}}{dE_{T_3}}}{\frac{1}{\sigma} \frac{d\sigma^{QCD}}{dE_{T_2}} \times \frac{1}{\sigma} \frac{d\sigma^{QCD}}{dE_{T_3}}}$$

one can see from the simulation that the background tends to accumulate in the left side of the plot while most of the top events have positive values, Fig.14a. The data, Fig.14b, appears as a mixture of the two.

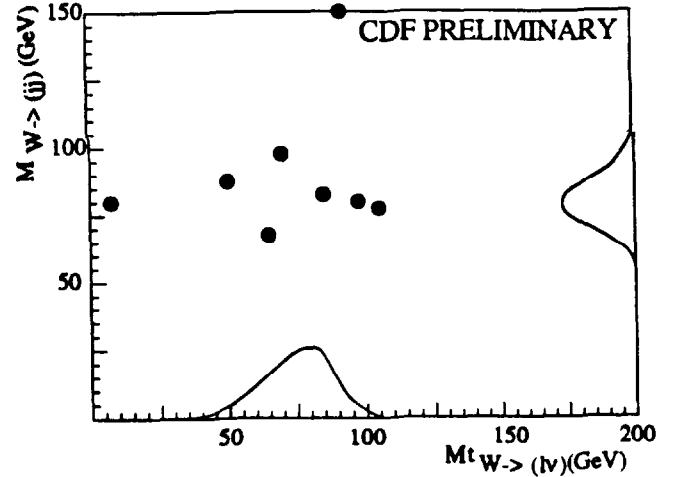


Figure 13:  $M_W(jj)$  versus  $M_{T_W}(l\nu)$  for the 8 events  $W + \geq 4$  jets with double tag.

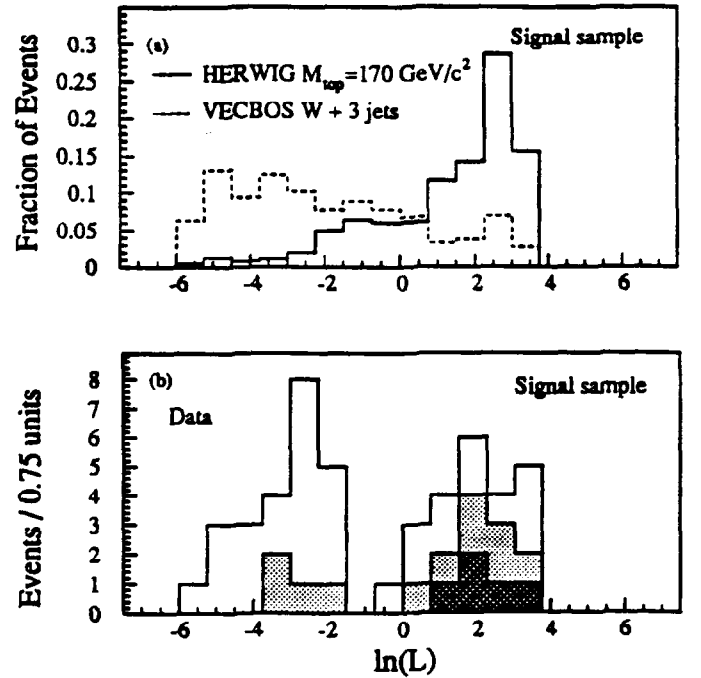


Figure 14: CDF  $L_{rel}$  distributions. Shaded area are tagged events, dark shaded for double tagged.

This is confirmed by the fact that the majority of tags (shaded events) are in the right side. Similar results obtain if one uses the variable  $H$  (scalar sum of all  $E_t$ , jets and leptons). Fig. 15a shows what is expected for top and for background when a  $W$  plus 4 or more jets are required. The data in Fig. 15b are consistent with a mixture of the two components. As before  $b$ -tags lie in the right side of the plot.

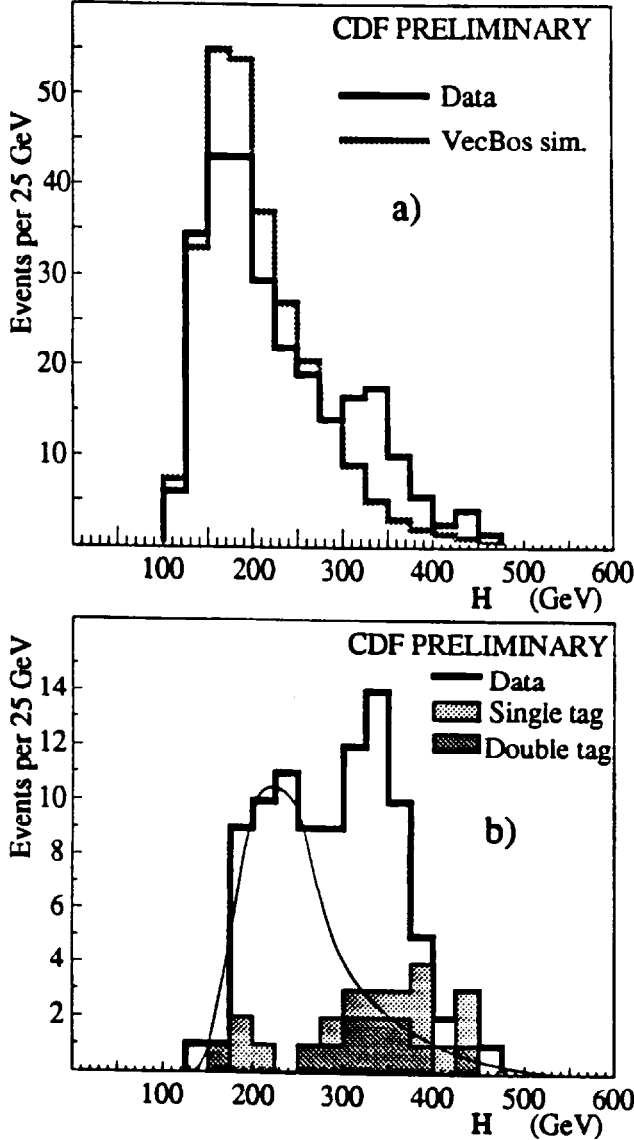


Figure 15:  $H$  distribution. Shaded area are tagged events, dark shaded for double tagged.

### 3.3 Six jets channel

On the basis of  $81 \text{ pb}^{-1}$  of CDF data a selection is made requiring at least six jets of at least 15 GeV and isolated by at least 0.5 units of rapidity. There are requirements on the scalar sum of  $E_t$  and aplanarity and at least one secondary vertex candidate tagging a  $b$ .

This last requirement is important to enrich the top sample and to reduce the combinatorial background in the mass reconstruction. Fig. 16 gives the result of this analysis for the sample with six or more jets (a), and (b) for the restricted sample with exactly six jets. In both cases an enhancement in the region of the top mass can be observed. The cross-section worked out from these distributions is  $9.7 \pm 3.3(\text{stat. only}) \text{ pb}^{-1}$  consistent with the published CDF value in Fig. 2. D0 also observes an excess in this channel when events are selected with a lepton tag in a jet and high  $H_t$ . The direct CDF and D0 measurement of the mass can be compared with what one can infer from precision measurement of other quantities related to the top mass in the Standard Model. This comparison is shown in Fig. 17 under the assumption of a Higgs mass of  $300 \text{ GeV}/c^2$ . This matter was discussed in detail in this conference, see for instance the report of A. Olchewsky <sup>6</sup> and bibliography therein.

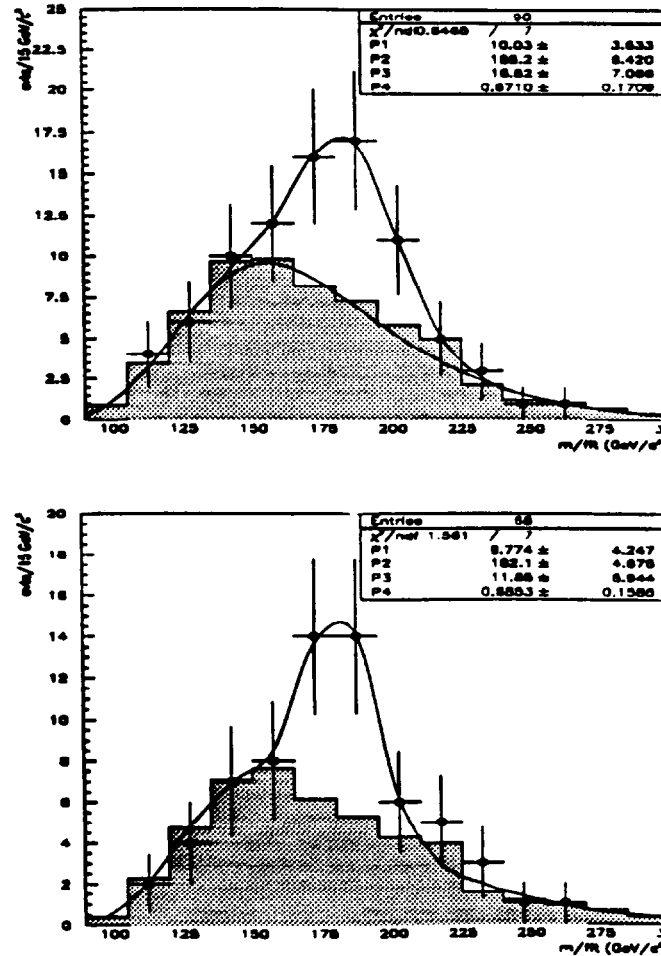


Figure 16: CDF mass distribution for all hadronic to candidates. Shaded area expected background.

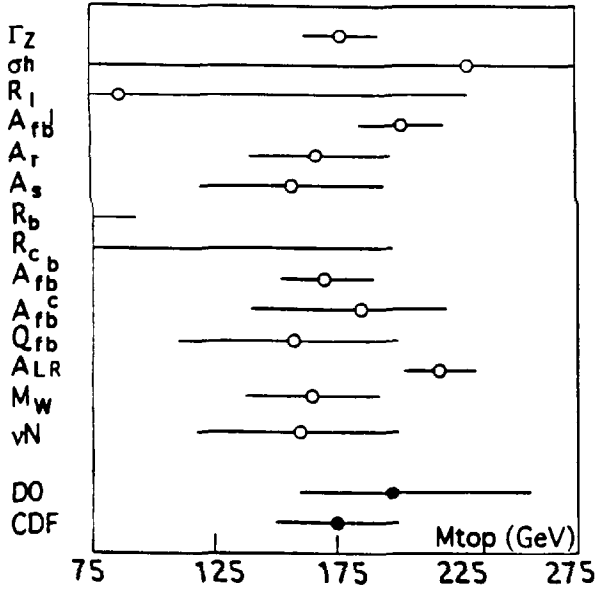


Figure 17: Comparison of CDF and D0 results with estimates based on precision electroweak data for a Higgs mass of  $300 \text{ GeV}/c^2$

#### 4 Expected improvements in the future

One of the main tasks is to determine with the best possible accuracy the central value of the top mass. Fig. 18 shows what CDF expects for the mass resolution under the hypothesis that only one  $b$  is tagged, that both  $b$ 's are tagged and that all partons are properly attributed, i.e. the best one can do to reduce the combinatorial background.

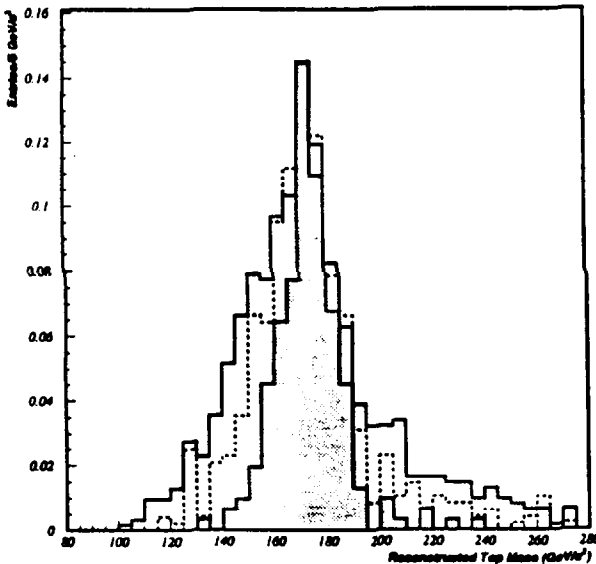


Figure 18: Distribution of constrained fit masses for HERWIG  $t\bar{t}$  events with  $M_{top} = 170 \text{ GeV}/c^2$ . The solid curve is the lowest  $\chi^2$  solution with one correct  $b$ , the dashed curve with two correct  $b$ 's and the shaded curve is the correct jet parton assignment.

Aimed to this goal there are a number of tools under study and, if effective, will be used in the mass determination:

**Looser tagging of the second  $b$  in  $b$ -tagged events.** In fact the SVX tagging algorithm is rather stringent, but it is reasonable to believe that if there is one  $b$ -jet, there should be a partner. One can tag as the second  $b$ -jet the one that is most likely to have a non zero impact parameter.

**Antitagging of light quarks.** Quarks from  $W$  decay can only be light (short lived) and one can associate with them the jets with a vertex consistent with the primary. These two studies use a variable called "jet probability". Promising preliminary results exist.

**Et ranking of jets.** For a heavy top one can see from simulations that  $b$ -jets tend to be the most energetic. This is evident since each top decays into a  $W$  and a  $b$ , then the  $W$  splits into two jets.

**Dispersion of the jet.** LEP results show that  $b$ -jets (and gluon-jets) are substantially wider than light quark jets<sup>7</sup>. The study of this variable, beside helping in the parton association of the decay chain has the potentiality to distinguish events where one of the selected jets happens to be a brems-gluon resulting in a wrong value of the mass.

**Jet charge assignment.** The "charge probability" of a jet has been introduced by Delphi<sup>8</sup> and successfully used in CDF in the analysis of  $b$  oscillations. It weights the charge of tracks with their  $p_t$  giving different probability for different charge. It is clear how the discriminating power of this variable improves with the jet  $E_t$ . In the case of  $t\bar{t}$  production and decay  $E_t$ 's are large and, given the sign of the lepton one knows the sign of all partons in the final state.

All the above studies, the increase of statistics between now and the end of the present run at the Tevatron, and a better understanding of the systematic uncertainties, makes one believe that in a year or so the error on the mass will be reduced by a sizeable fraction. Much more should come in forthcoming Run II.

An increase of energy from 1800 to 2000 GeV, already brings an improvement of the top yield by 35%.

An increase of luminosity should allow each experiment to collect a factor 5÷10 more statistics.

Both experiments are planning important upgrades. Among these, relevant to top physics are: for CDF, a new vertex SVXII with two dimensional read-out, increased coverage, and improved vertex capabilities. Also planned are an intermediate fiber tracker widening the tracking acceptance, new plug calorimeters, and new forward muon detection system giving almost full angular acceptance for electrons and muons. D0 is also planning and preparing important upgrades: a silicon vertex device, a solenoid providing magnetic field in the tracking volume where a new tracking system based on scintillating fibers will be installed, and a preshower detector in the forward region.

Taking into account all the above one can conservatively say that when both experiments will have an integrated luminosity of  $1\text{fb}^{-1}$  the mass of the top will be known with an uncertainty smaller than 3 GeV and the error on the cross-section will be below 10%. When LHC will start operations there are no doubt that the amount of top quark produced there will soon exceed that collected in the interim at the Tevatron. This can be seen in Fig. 19 showing that the cross-section at LHC is two orders of magnitude higher <sup>9</sup>.

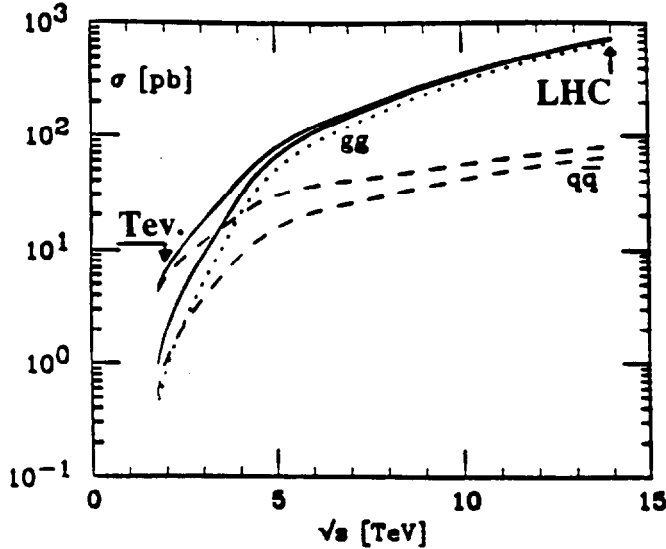


Figure 19: Energy dependence of the cross section of production of  $175\text{ GeV}/c^2$  top quark in  $pp$  and  $p\bar{p}$  collisions.

On the same picture, however, one sees that at LHC top production is dominated by  $gg$  interactions while at the Tevatron  $q\bar{q}$  annihilation dominates. This knowledge of the initial state makes the Tevatron the only machine where studies of the production mechanism are possible and can extend the interest of experiments there even in the LHC era.

## 5 References

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